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DEVELOPMENT OF A MICROINCH ACTUATOR

Contract NAS 1-7018
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DEVELOPMENT OF A MICROINCH ACTUATOR

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Farmingdale, New York 11735

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Langley Research Center
Hampton, Virginia

ABSTRACT

The Republic Aviation design concept for a microinch actuator has been tested and proven to have definite merit. Several problem areas arose during fabrication and testing of the device. Correction of these problem areas has resulted in a functional microinch actuator. This report fully describes the problem areas, their interactions and the corrective measures taken to make the device a functional reality.

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SECTION I

INTRODUCTION

This Final Report is presented upon completion of Contract NAS 1-7018 issued by the Langley Research Center of the National Aeronautics and Space Administration.

In the first phase of this contract, the Republic Aviation Division of the Fairchild Hiller Corporation untertook to develop and manufacture three microinch actuators, each actuator having the capability of:

- making displacements of one-half microinch (5×10^{-7} inches) per step
- moving at a rate of 3×10^{-4} inches per second, and
- working against an opposing force of 1000 grams (2.2 pounds)

The results of the work were reported in the Final Report NASA CR66626 entitled, "Development of a Microinch Actuator", by Mr. John M. Varga, dated March 24, 1968.

An extension of this contract modified the requirements as follows:

- minimum displacement of one-half microinch (5×10^{-7} inches) $\pm 2.5 \times 10^{-7}$ inches with each individual step not varying more than ± 10% of the commanded displacement.

- in order to initially position the modified actuator, it shall be able to move at a rate equal to or greater than 3×10^{-4} inches per second by varying the step size and/or step rate.
- the modified actuator shall be capable of working against an opposing force equal to or less than 5000 grams (11 pounds) and,

- the cross sectional area shall be such that the actuators can be mounted on three inch centers.

Based upon prior experience in the field of electrostrictive devices, the Republic Aviation Division of the Fairchild Hiller Corporation approached this problem by utilizing a piezoelectric "inching" unit with successive clutches. The nature of the piezoelectric action results in small linear displacements, adequate force levels and moderate frequency response, all of which are ideal for the special requirements to be satisfied by the microinch actuator. However, the small displacements and their interactions require tolerance criteria and machining techniques which severely push the state-of-the-art. The relationship of these criteria and techniques to the practical design, fabrication and functionality of the microinch actuator will be discussed in this report.

SECTION II

DEVICE CONFIGURATION AND OPERATION

The configuration of the microinch actuator, developed and manufactured under this contract, is illustrated in Figure 1. This illustration shows that the device consists of four components which are: - two clutching units, an extender-contractor unit and the housing unit. The clutch and the extender-contractor units make use of the converse piezoelectric effect, i.e., a mechanical strain (deformation per unit length) produced in a crystal or ceramic due to electrical stress. Figures 2 and 3 are photographs of a disassembled and partially assembled microactuator device.

The sequence of events to cause a linear displacement of the actuator is as follows and is illustrated in Figure 4.

1. With no voltage applied the clutches B and C exert a compressive force on the walls of the microactuator housing. The piezoelectric clutch stacks are in compression due to a controlled interference fit between the housing and the clutch faces.

2. Voltage applied to clutch B causes the unit to contract to less than the unstressed distance between the housing walls releasing the upper protion of the extender-contractor unit.

3. Voltage applied to A, the extender-contractor unit, causes this element and clutch B to expand upward.
4. Voltage removed from clutch B locks that clutch in its new position
5. Voltage applied to clutch C releases the lower portion of extender-contractor, A.

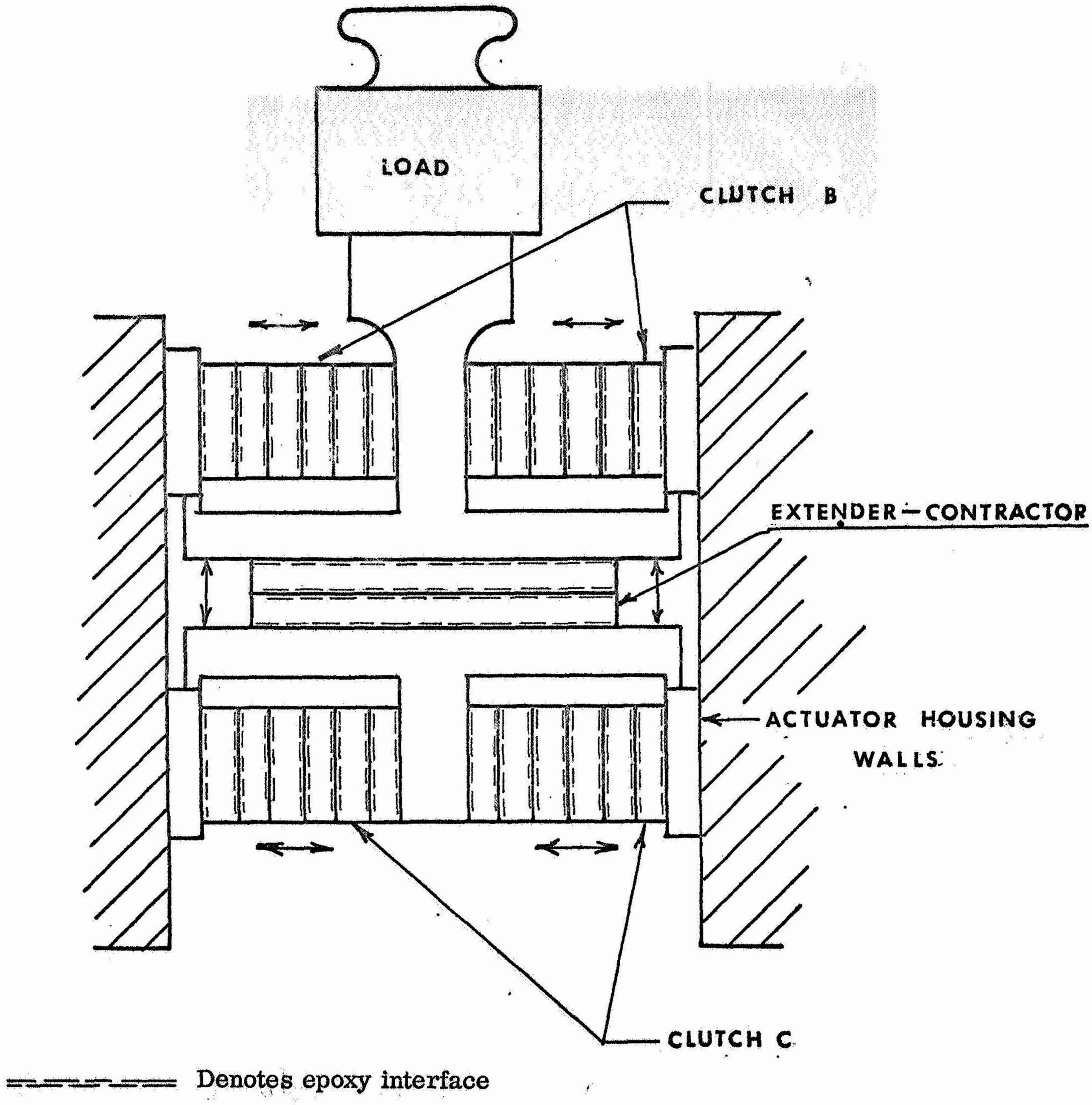


Figure 1. Conceptual Configuration of the Microinch Actuator

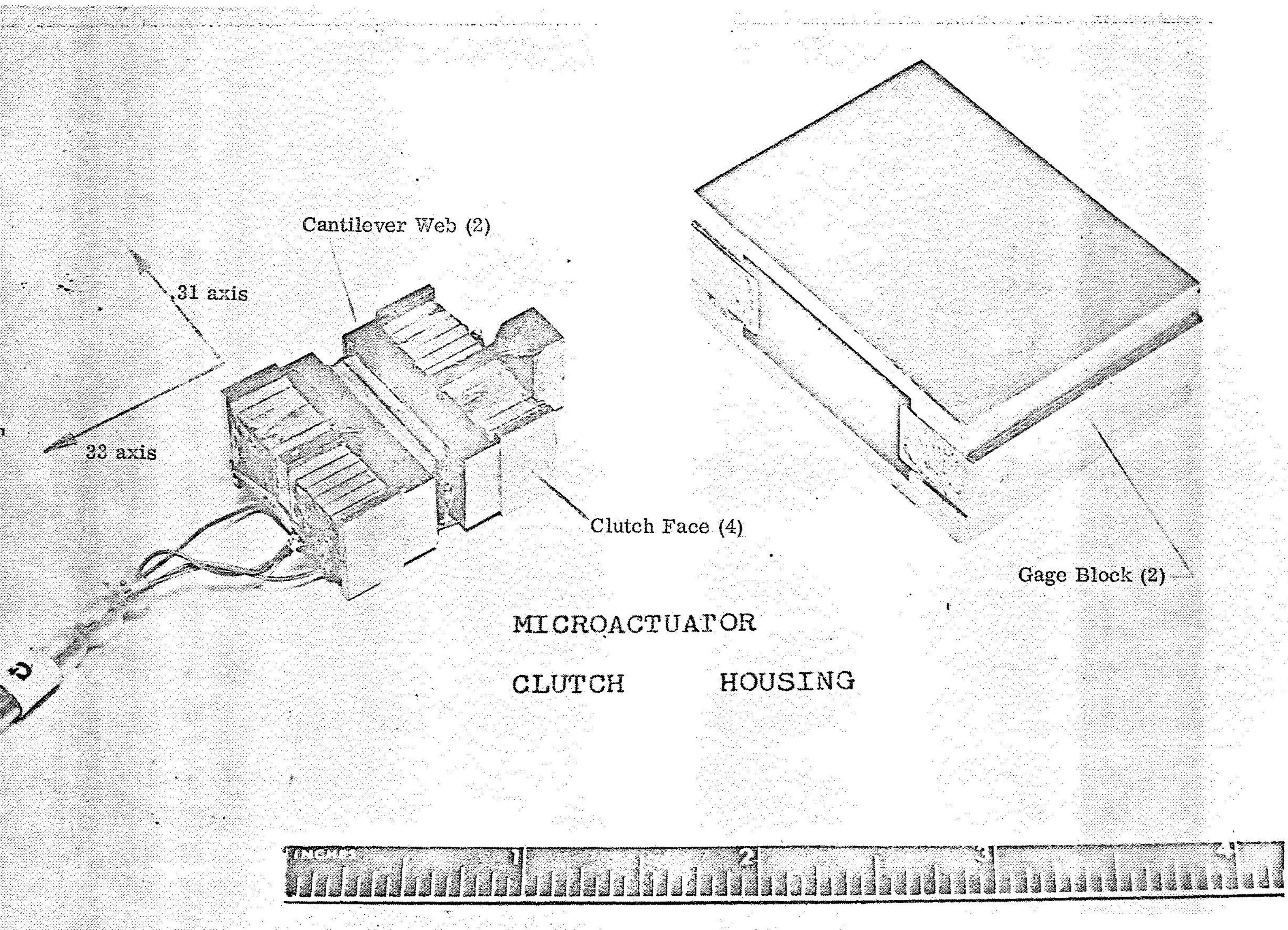


Figure 2. Microinch Actuator (Disassembled)

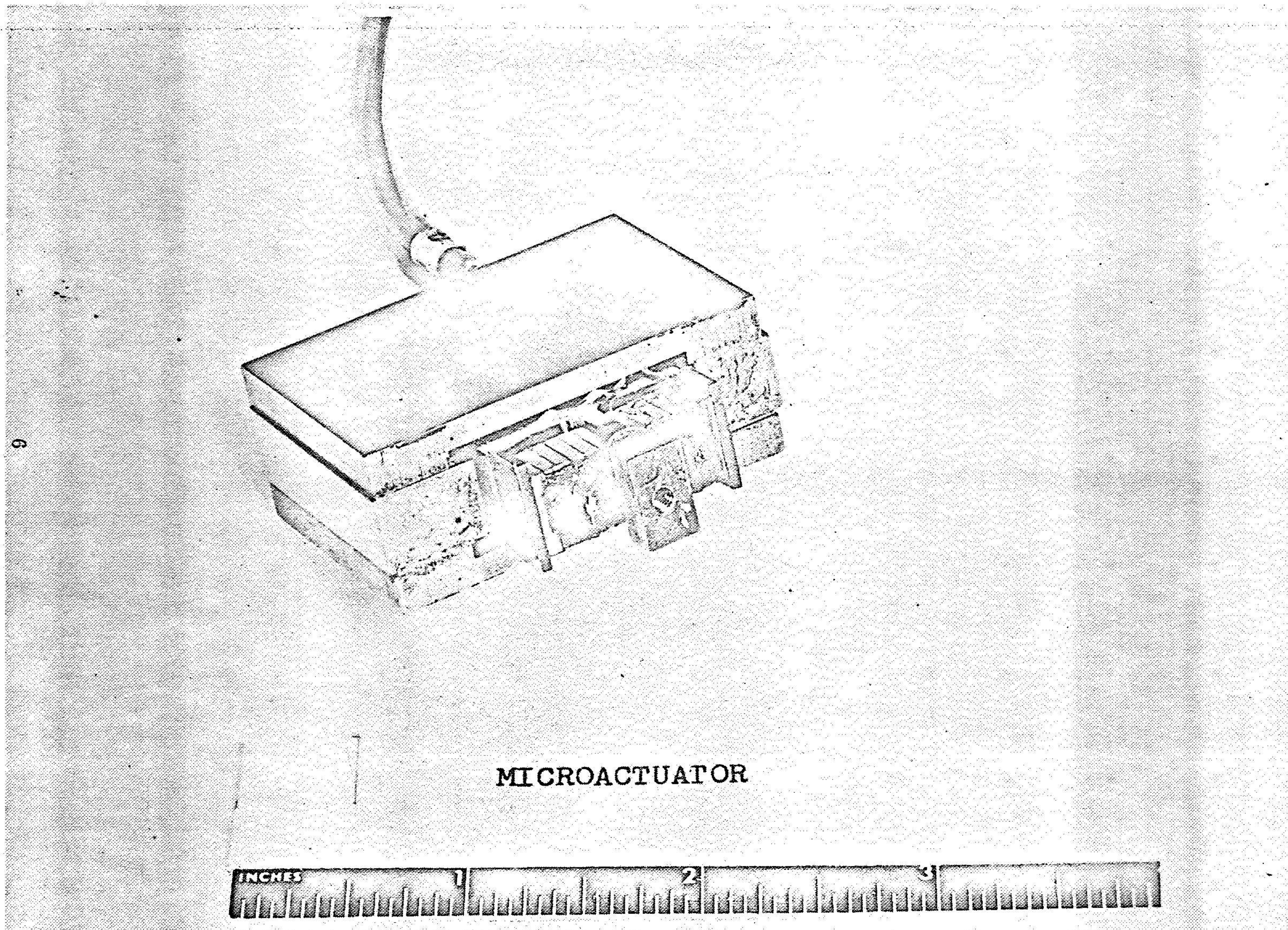
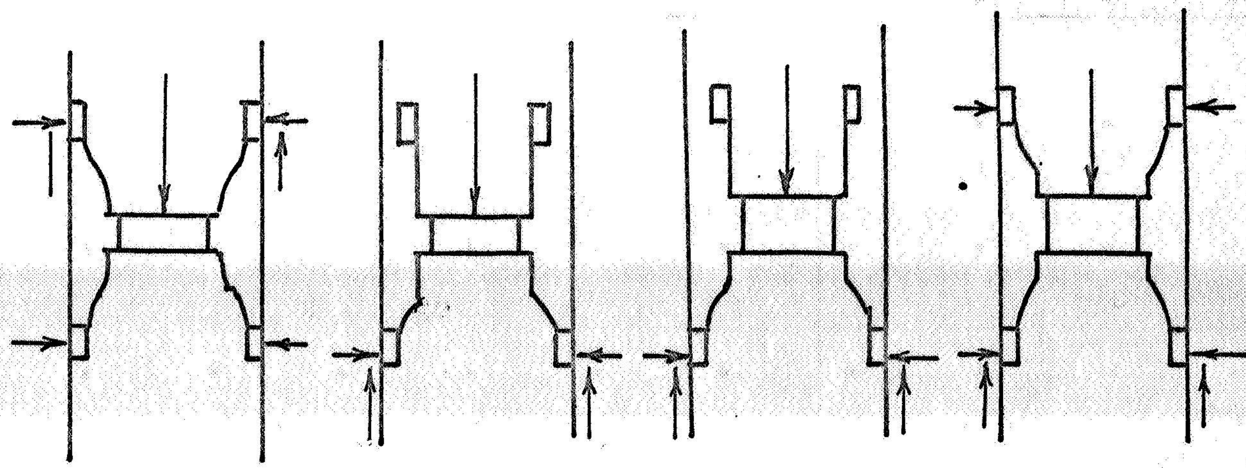
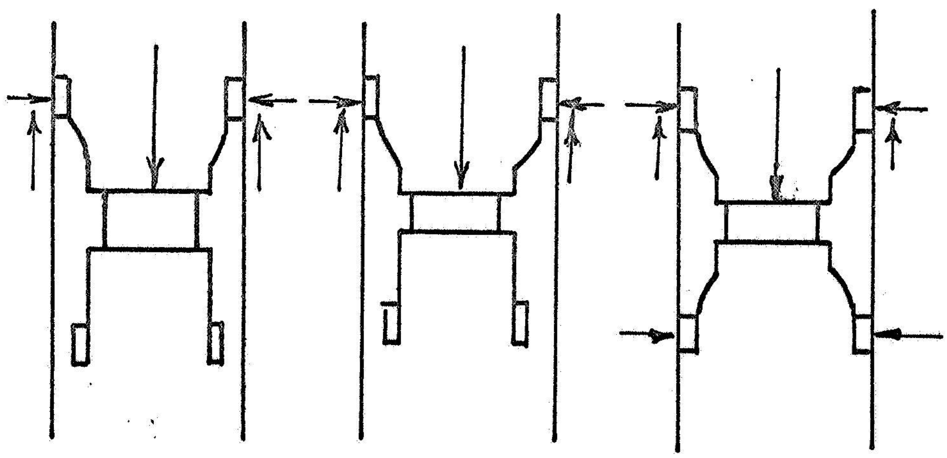


Figure 3. Microinch Actuator (Partially Assembled)



	(1)	(2)	(3)	(4)
Upper Clutch	Engaged	Free	Free	Engaged
Lower Clutch	Engaged	Engaged	Engaged	Engaged
Extender Contractor	Contracted	Contracted	Expanded	Expanded



	(5)	(6)	(7)
Upper Clutch	Engaged	Engaged	Engaged
Lower Clutch	Free	Free	Engaged
Extender Contractor	Expanded	Contracted	Contracted

Figure 4. Operational Sequence Schematic

6. Voltage removed from A allowing it to return to its original length which pulls the lower protion up to the upper section.

7. Voltage removed from clutch C causes it to lock between the housing walls. The one-step extension $\geq 5 \times 10^{-7}$ inches has now been obtained between the outer actuator housing and the center clutch assembly.

To obtain a contraction of the unit, the same voltages are applied in the same polarity to the unit but starting with the release of clutch C, thus:

1. No voltage - unit locked in position
2. Activate or release clutch C
3. Extend Unit A (downward)
4. Deactivate or apply clutch C
5. Activate clutch B
6. Unit A to normal length
7. Deactivate clutch B

Since the voltage applied to the extender is relatively small (10.73 volts for 5×10^{-7} inch displacement) an additional "high speed" mode of operation is available on the actuator. By simply switching part or all of the clutch voltage onto the extender-contractor, a larger step per pulse will be produced and the actuator can traverse a larger distance per given times.

Two individual control consoles were manufactured under this contract, one having a variable voltage equivalent of 0.0-20.0 microinches per step and the second having three different voltages corresponding to 0.50, 1.0, and 5.0 microinches per step.

SECTION III

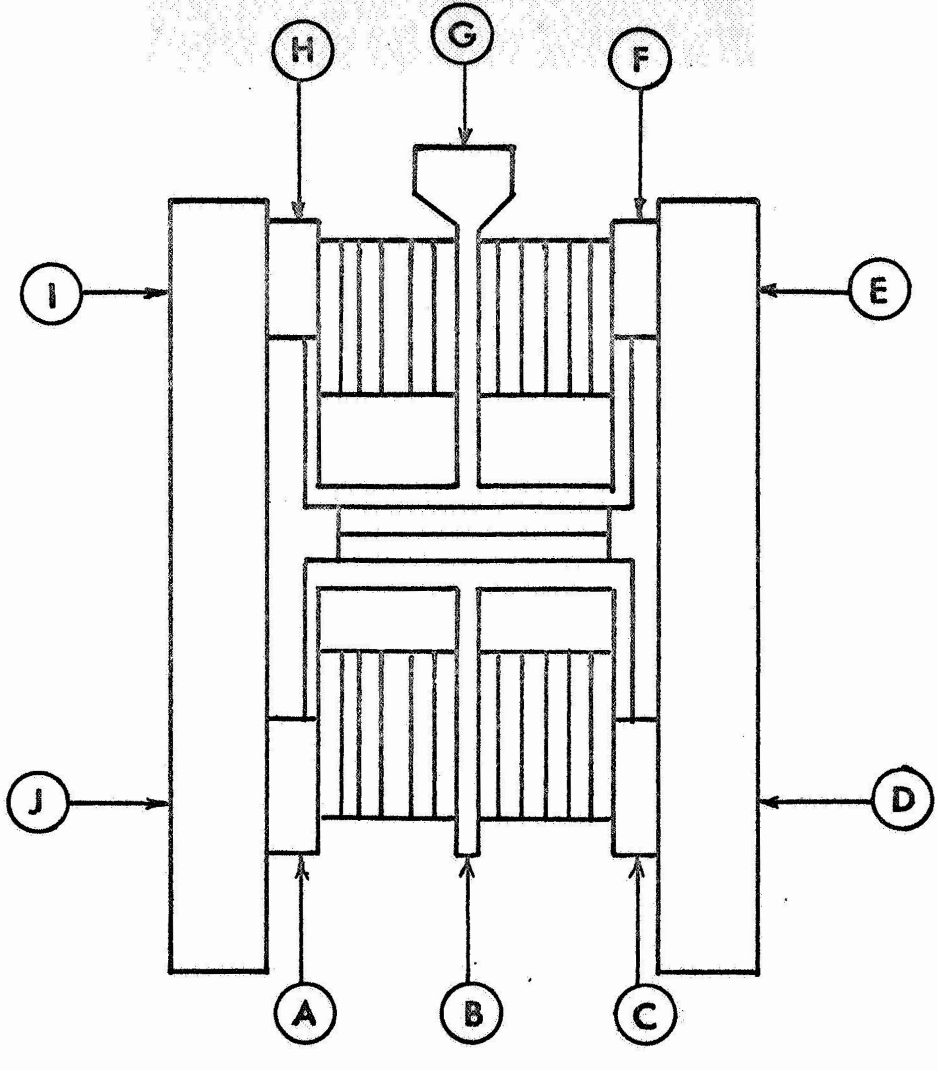
OPERATIONAL CHARACTERISTICS

Under the original contract, three microactuator devices were constructed. These devices were identical in construction as per the drawings in Final Report NASA CR66626. All of the devices were capable of walking upon command and one device could support up to three pounds when the clutches were used in the extender mode. However, the device was designed with the clutches in mechanical compression in order to exert a mechanical force with no electrical power consumption. In the compression mode, the devices could only support 100 to 500 grams before slippage occurred. Device operation tended to be sporadic in nature. Consequently, diagnostic deflection data was taken with an operable actuator in order to determine the problem areas.

The diagnostic instrumentation consisted of a Pratt & Whitney Opt-O-Limit gage coupled to a magnetic amplifier and pen recorder. The sensitivity of the pen recorder was varied by using a variable load resistance. The resolution of this system is estimated to be better than 2×10^{-7} inches. A diagram of the various positions where diagnostic deflection data was taken is shown in Figure 5. The compilation of averaged deflection data is shown in Table 1. Representative diagnostic traces are included in the Appendix. The scale factor for these traces is not constant due to the variable load resistances used. Negative deflections in the top and bottom clutches indicate movement into the housing. Negative deflections in the side walls of the actuator housing indicates a drawing together of the walls. All readings are in microinches. It should be noted that the deflection data for the top and bottom clutches are not equal. This is due to the elastomeric nature of the conductive epoxy in the extender/contractor stack.

Examination of the data shows that as the top clutch is released the invar cantilever bows. This bowing (positive deflection on H, F, A, C, and negative deflection on G and B) is probably due to the following reasons:

a) The clutch is a cantilever whose rigidity restricts the clutch motion where the cantilever web joins the clutch faces. This type of action causes the clutch face to contact the housing wall in a line contact on the end of the clutch face joining the cantilever web. Actuating the device causes the clutch to rock around the line contact alternately bowing in and out. This will be more fully discussed with the section on interference fit.



B = BOTTOM CLUTCH

G = TOP CLUTCH

PRATT & WHITNEY OPT-O-LIMIT GAGE
ACROMAG 190 D.C. AMPLIFIER
BAUSCH & LOMB RECORDER

Figure 5. Diagnostic Deflection Data Test Points

TABLE I. MICROACTUATOR ANALYSIS DATA
(Deflections in μ inches)

	Position		EFFECT Side	Top Clutch			Side	Side	Bottom Clutch			Side
	Operation		I	H	G	F	E	J	A	B	C	D
Going Up	Release Top	(RF)	-6.3	+ 8.3	- 8.2	+11.8	-5.8	-0.9	N.D.*	+ 3.7	N.D.*	+0.2
	Extend	(E)	-	+11.9	+17.7	+17.2	-	-	"	+ 6.2	"	-
	Hold Top	(HF)	+5.8	-10.6	+ 4.3	- 2.0	+3.3	-	"	- 1.4	"	-0.5
	Release Bottom	(RR)	+0.4	+ 8.2	+ 4.0	- 7.6	+1.4	-6.6	"	- 8.0	"	-5.0
	Retract	(R)	-0.3	-	-	-	-0.4	-	"	-23.5	"	-0.1
	Hold Bottom	(HR)	-0.6	- 0.9	- 2.1	- 1.1	-0.7	+7.0	"	-	"	+4.7
	Net Deflection				+15.7					-23.0		
Going Down	Release Bottom	(RR)	+1.1	+10.5	+ 8.2	- 4.9	+0.7	-5.9	+9.1	- 9.2	+12.3	-5.5
	Extend	(E)	-0.1	-	+ 3.0	-	-	-0.1	+17.0	+22.1	+23.6	-0.4
	Hold Bottom	(HR)	-0.9	- 1.4	-1.0	-	-1.0	+6.7	- 3.6	+ 4.3	-11.5	+4.5
	Release Top	(RF)	-6.7	+ 8.5	- 7.5	+13.3	-5.2	-0.7	- 0.5	- 3.4	- 0.2	-
	Retract	(R)	-	+23.9	-24.6	-18.0	-0.2	-0.3	-	- 0.6	-	-
	Hold Top	(HF)	+ .53	-16.5	-	- 9.2	+3.8	-0.2	- 0.2	- 2.0	- 0.7	-0.2
	Net Deflection				-21.9					+11.2		

* N.D. - Not Determined

NOTES:

1. Vertical Deflections are positive: { up for the top clutch; down for bottom clutch }

2. Lateral Deflections are positive outward from centerline of

3. Letters in parentheses denote abbreviations on data sheets of the Appendix

b) Our latest experiments have let us to the conclusion that spurious action of the clutches may well be due to a conductive epoxy cement which was used to fabricate the clutch stacks. Refer to Figure 1. This epoxy turned out to be elastomeric in nature which means that it would be spondy, have a low spring constant and low shear strength. We believe that this is the cause of the inability to support a load and the spurious clutch movements.

c) A contributing factor to the spurious clutch movement is that as the piezoelectric stack contracts in the 33 axis (clutch working direction) the stack expands in the 31 axis (clutch walking direction). This action in the 31 direction becomes a contraction when the clutch is put in the "hold" position. This expansion and contraction is limited to ±5 microinches. This behaviour of the piezoelectric ceramic is a design limiting criteria which must be reckoned within a redesign of the device. Refer to Figure 2.

The data also shows that as the clutches are actuated, the microactuator housing walls move in and out. The less deflection the side walls undergo on clutch activation, the more the clutch face rises and the more the face extends when the extender is actuated. The side walls do not return to their original position. The housing used in these determinations were epoxied together using Hysol 1C. Subsequent determinations showed that this epoxy sprung upon clutch release. It should be noted that some movement of the housing walls is due to the fact that the housing web (tool steel pieces joined to the gage blocks) deform due to the tensile force placed upon them by the clutches. This deformation is governed by the modulus of elasticity of the tool steel, and the webs cross-sectional area. This topic will be further explored later in this report.

Examination of the data for G and B show that the deflections caused by the application of the 400 volts to the extender-contractor stack is in fair agreement with the theoretical extension-contraction which is: 400 volts x 2.34×10^{-8} inch/volt for two slabs = 18.7×10^{-6} inches. Here again, small spurious movements (6-8 micro-inches) are in evidence for each slab.

Two of the microactuator units were sent to Republic for test purposes. Of these, one was operable and the other was locked and inoperable. The operating unit operated sporadically and was unable to support a load in excess of 100 grams. The inoperable actuator was freed and found to have a separated epoxy joint on the extender-contractor and a rusted area on the bottom clutch-gage block interface. The rusted area appears to have been caused by a fingerprint.* Metallographic polishing of the gage block face revealed an etched condition, which would require heavy grit polishing for its removal. Microscopic examination of the clutches and gage blocks reveals horizontal indentations in clutches and blocks caused by (1) running the clutch past the housing ends, and (2) line bearing contact between clutch face and block. This examination also showed deep scratches caused by dirt particles and one spot that looked like an arc or spark crater. It is clearly evident that a device that operates on such minimal clearance requires a cleanliness typical of quality optical practices. The finished device should have electrical travel limiting switches, common flexible bus ground, dust caps and be assembled with extreme care in cleanliness.

Microactuator housings using new standard hardened gage blocks for the housing walls were assembled around each of the two clutches. The assembly technique described in the following section was used. The clutch assembly which was functional was able to walk in the new housing. The other clutch assembly (the one which had been locked) was unable to walk in the new housing after its extender-contractor was fixed. Room temperature fluctuations caused the clutches to lock in the steel housing when the temperature rose and to become loose in the housing when the temperature fell. The total temperature excursion was only 2-3°Centigrade for these effects.

It became evident during the operation and testing of the device that the design concept had worked and that a thorough detailed examination of the theory and materials of construction and their interactions and behavior was required in order to make the device a truly functional reality.

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* Note fingerprint in photo on Fig. 2.

With this goal in mind, the system was rigorously tested, analyzed and where possible re-synthesized to eliminate weaknesses. The discussion will continue with a breakdown of the actuator into its component parts, their design and usage.

SECTION IV

THE PIEZOELECTRIC CLUTCH

A. CONSTRUCTION

The unit consists of piezoelectric ceramic stacks mounted in an invar cantilever spring. Each stack consists of six Clevite PZT-5H piezoelectric ceramic slabs (0.300" x 0.375" x 0.060"). The sides of each slab are silvered. Electrical hookup and mechanical assembly of the stacks was accomplished by use of copper foil cemented between the ceramic slabs with a conductive epoxy cement, Dynaloy 325A and B. The ceramic is used in the compression mode, whereby the load supporting force is accomplished by an interference fit between the clutch faces and the housing gage blocks when there is no voltage applied to the stacks. Application of voltage to the stacks results in increased stack compression and clearance for clutch movement. The negative terminal of the power supply and the invar are connected to the ground. The positive pole of the piezoelectric slabs is connected to the ground. The ceramic pieces are wired in parallel in order to provide the largest linear displacement with low working voltages.

B. DESIGN CONSIDERATIONS

This device works by making use of an interference fit to support a load. Design data for the piezoelectric ceramic material, Clevite PZT-5H shows that the material must not be compressively stressed in excess of 1500 pounds per square inch. The maximum allowable interference fit for this compressive stress must not exceed a total of 33 microinches across each clutch. Since the piezoelectric ceramics are in parallel, the voltage across each ceramic piece must approximate 120 volts for this interference fit. Theoretically, this interference fit should provide for load support up to 30 pounds assuming an average coefficient of sliding friction. The actual load support capability of the device was less than one-half pound. Therefore, an investigation was made into the factors that affect load support, i.e., interference fit.

C. PARAMETERS AFFECTING OPERATIONAL BEHAVIOR

1. Cantilever Constraint

The very nature of the cantilever spring design restricts the clutch movement, therefore, the true amount of clutch travel as a function of applied voltage was determined experimentally and is shown in Figure 6. The data shows that the invar cantilever spring restricts the movement of the clutch face edge at its juncture with the invar web. This constraint by the rigidity of the invar amounts to approximately 50% of the expected clutch throw. It is this rigidity and constraint of clutch motion that accounts for the line contact of the clutch face and the gage blocks and for the bowing of the cantilever spring resulting in spurious clutch movements.

During the development of the device, the only method for fitting the housing to the clutch so that it could work consisted of putting the piezoelectric clutches in compression with 300 volts and using the compressed clutches as a jig, setting the housing gage blocks with an epoxy cement (Hysol 1C) to the housing tool steel webs. The voltage had to be kept on the stacks overnight for the epoxy to cure. An operating voltage of 400 volts was then used to provide clearance for clutch travel. Many times the clutch was too loose in the housing and could not operate. It should be noted that the differences in interference fit at the line contact from 300 to 400 volts is a total of only 20 microinches. The clutch stacks had to be electromechanically overstressed 200 to 300% in order to provide this interference fit.

The functioning clutch assembly was undercut 0.020" into the invar spring just below the juncture with the clutch faces in order to provide:

- a. the same interference fit with less stress, or
- b. increased interference fit which would increase the ability to support a load.

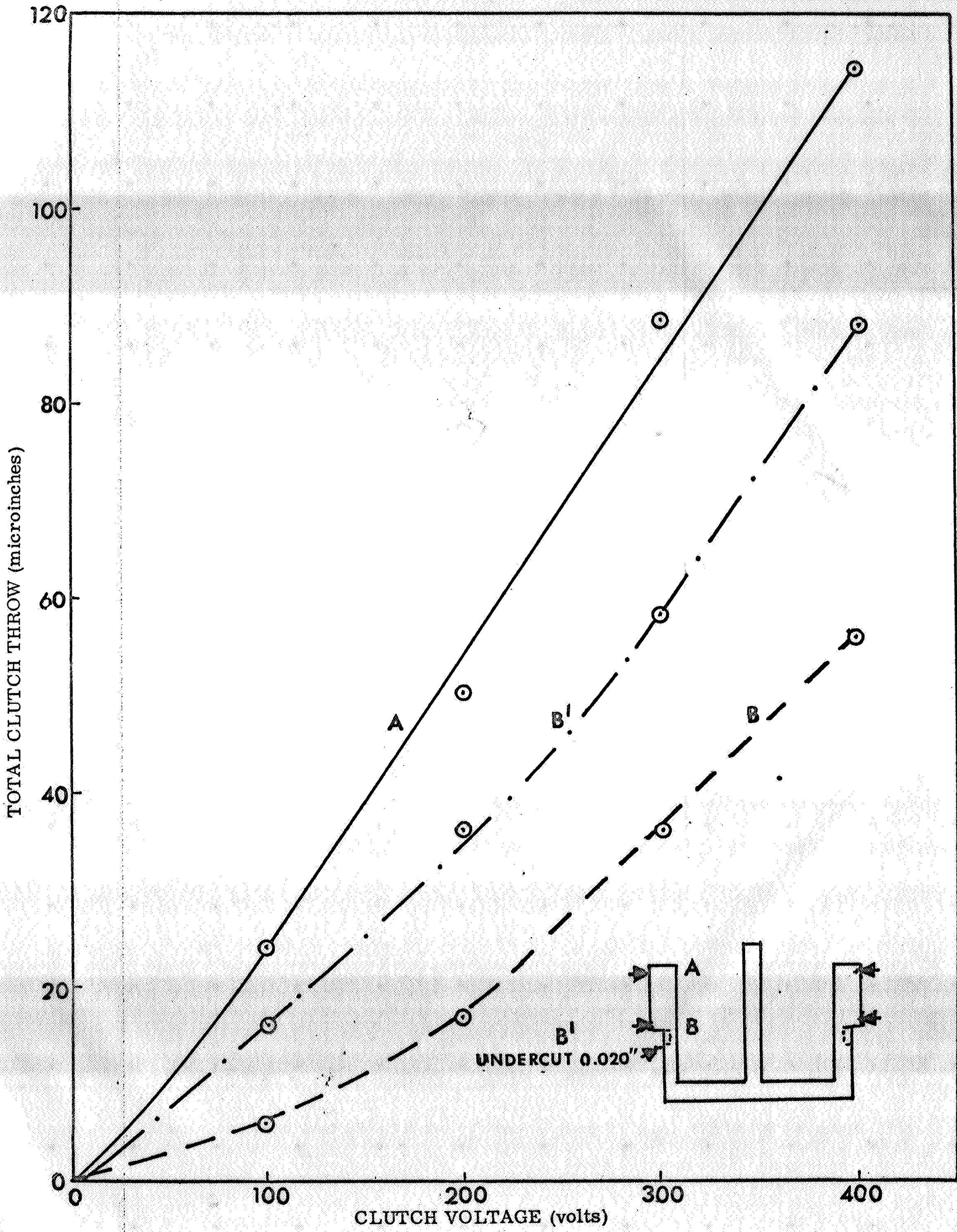


Figure 6. Total Clutch Throw as a Function of Clutch Voltage

Deflection data in Figure 6 shows the available interference fit at the line contact point to be increased from 20 to 30 microinches for the same electrical conditions as used with the original clutch. This undercut clutch, when assembled with a fitted housing could not support a load in excess of 200 grams and its operation was sporadic in nature.

The technique for fitting the housing to the clutches was responsible for the compressive overstress. Ideally, since the clutches were precision lapped parallel to within 5 microinches, a spacer stack of gage blocks should be used to provide an adequate interference fit with assured parallelity of ways. This technique could not be made to work until the reason for its failure became known during temperature testing of the clutches.

2. Dimensional Changes in the Clutch

Dimensional changes in the clutch have been found to be due to:

- the elastomeric conductive epoxy used to cement the piezoelectric stacks
- depolarization of the piezoelectric ceramic
- temperature changes and mismatch in the coefficients of linear expansion of the device construction materials

All of these reasons for dimensional changes will be discussed in this section.

a) Elastomeric Conductive Epoxy Cement

A microactuator unit was made up of the undercut piezoelectric clutch and the stainless steel webs 3/8-inches thick. The gage blocks were epoxied in place by setting 300 volts on the clutches in order to contract them. Room temperature was 75°F when the blocks were set, and allowed to cure overnight. In the morning, at 75°F temperature, the actuator operated for a distance of 1/8-inch at only one location within the housing. It was suspected that the microactuator clutches were not identical in dimensions and therefore the ways had a slight angle to each other. Advancing the unit into the angle apex caused the unit to lock and withdrawing the unit from the apex caused the outer clutch to disengage the gage blocks.

Using a stack of gage blocks as a means of obtaining parallelity of ways with a constant dimension, the ways were set at the dimension of the top clutch of the undercut clutch assembly. When the epoxy cured, the top clutch fitted the web assembly snugly, the bottom clutch would not enter the assembly. Consequently, it was decided to accurately measure the distance across the clutch faces as a function of temperature. Using an oven that could control temperature to ± 0.2°C the clutches were heated and equilibrated at various temperatures above room temperature. The clutch was removed from the oven and placed under the Opt-O-Limit gage. In this way, the dimensions across the clutch faces for both the undercut clutch assembly and the untouched clutch assembly were determined as a function of temperature. The curves are shown in Figure 7. They show that the top clutch of the undercut clutch assembly is approximately 50 microinches smaller than the bottom clutch of the same assembly. The untouched assembly has approximately 150 microinches difference.

These differences occurred on both clutch assemblies and one fact concerning the assemblies immediately became apparent. It is that:

- The two clutch assemblies were once lapped so that opposite clutch faces were parallel to within one second of arc (0.000005 inches per inch length) and both clutches on each separate assembly were identical in dimension. The one clutch assembly that has ever worked was the one that had the smallest difference in dimensions. This unit was undercut to allow more linear displacement when activated. The

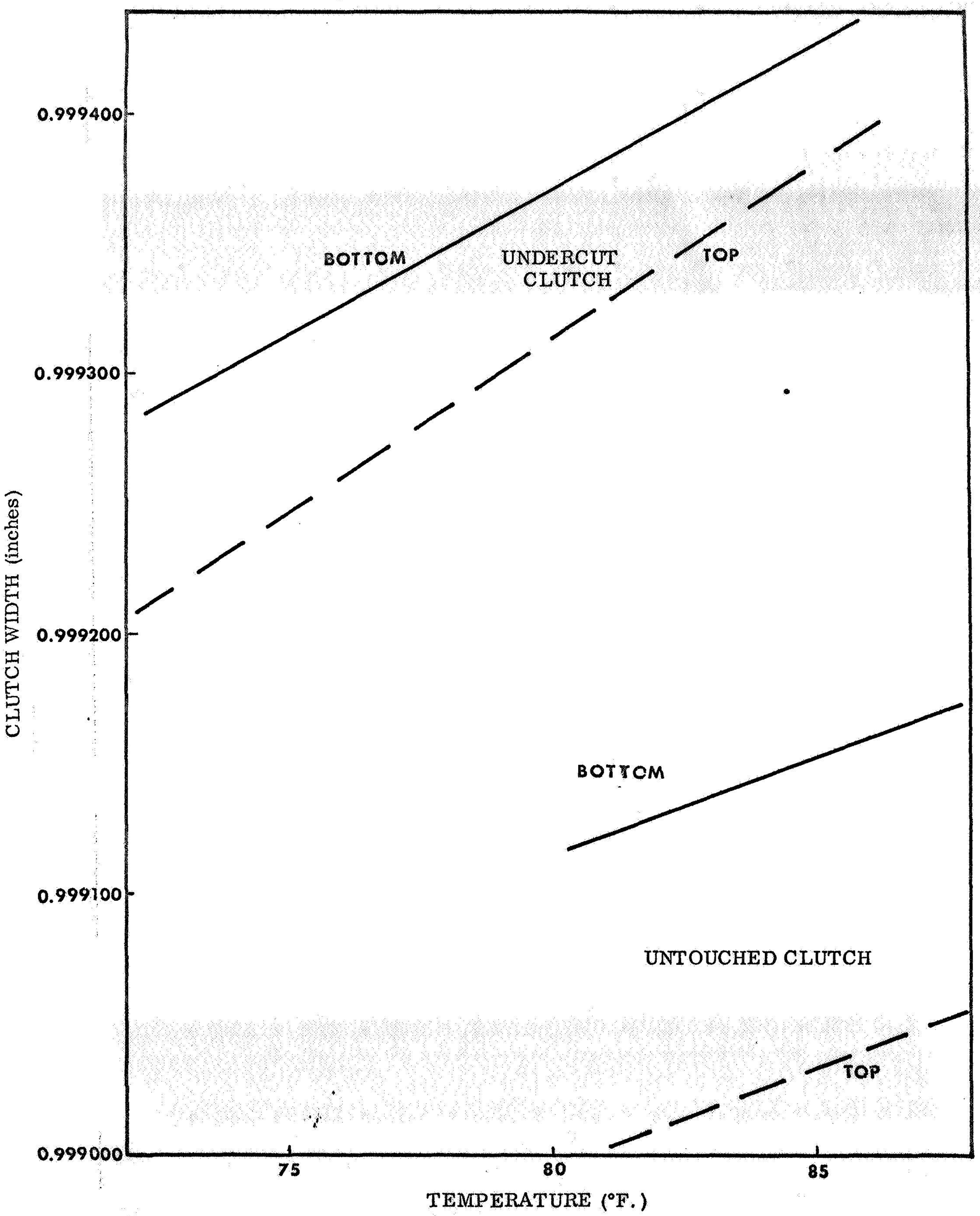


Figure 7. The Effect of Temperature on Piezoelectric Clutch Width

other unit was used as a backup control and therefore was not modified. Apparently, dimensional changes have taken place in both clutches.

These dimensional changes could have been caused by:

- The uneven flexing of the clutch faces due to the rigidity of the invar cantilever spring,
  and/or
- uneven flexure in the piezoelectric ceramic stacks
  and/or
- that the clutches had not been electrically cycled sufficiently to an equilibrium state prior to precision lapping
  and/or
- the conductive epoxy used to cement the piezoelectric clutch stacks was changing dimensions.

Experimental data supported the conclusion that this latter factor appears to be the case.

Subsequently, the undercut clutch assembly was precision lapped so that its opposite faces were parallel to within 10 microinches, a surface finish of 2 microinches r.m.s. and with the dimension across the clutch faces some multiple of 25 microinches. Gage blocks are only available to some multiple of 25 microinches, i.e., 0.100025, 0.100050, 0.100075, and 0.100000 inches. The microactuator was reassembled using the gage blocks as interference fit and parallelity spacers. The interference fit was selected so that no more than 180 volts was placed across the clutch. The microactuator unit walked for 250,000 cycles backwards and forwards over 1/4 inch travel. The unit would not support a load and careful dimensioning of the clutches and the housing in relation to the original gage block spaces showed that the dimension of the clutches across the faces tends to take the set of the housing. Clearly, we have controlled in large part, the sporadic operation of the microactuator device and with this control should come the control of the load support ability. It should be noted, that with the revised technique for the fitting of the housing to the clutch, the clutch has not dropped out of the housing when the room temperature changed.

It was at the suggestion of the NASA Technical Monitor that we contacted the General Electric Company regarding piezoelectric ceramic stability. The General Electric investigators had found that their stability problems were due to the eopxy cement used to bind the piezoelectric ceramics together in a stack. As a consequence of this discussion we contact the manufacturer of the epoxy (Dynaloy, Inc.) and found that the material used to fabricate the clutch stacks (Dynaloy 325 A&B) was an elastomeric material. The manufacturer could not supply us with any engineering data concerning this material but they did suggest the use of a different catalyst that would provide a rigid bond.

Elastomeric materials are spongy in nature and would be assumed to have a very low spring constant. Essentially, the microactuator clutch is composed of metal, piezoelectric ceramic and the epoxy material. The metal and ceramic have much higher spring constants than would be expected from elastomers, therefore, we have a situation of three materials in series one of which could have a low spring constant. The linear displacement caused by the piezoelectric material could be absorbed by the elastomer with little or no force transmitted to the housing walls. This factor could very well be the cause of poor load support by the microactuator units.

The microactuator clutch that had never functioned was taken apart after softening the conductive epoxy with a solvent. Examination of the silvered faces of the ceramics and the copper shim showed that they were cross hatched with a scalpel in order to provide pockets to trap and confine the conductive epoxy within the layers. The setting of the micro-ridges of this cross hatching on top of one another with the conductive epoxy as a sandwich accounted for 0.030 inches in a total of 0.403 inches. Each piezoelectric ceramic stack contained 30 mils of small spring constant conductive epoxy and micro-surface contact area moderate elastic modulus, copper. The clutches have been rebuilt with a more rigid adhesive and nickel shims. Across the new clutch stacks, in the adhesive interfaces, there is less than one mil of adhesive. When the clutches are assembled into a unit, the clutch faces are precision lapped according to specifications. We believe that this unit will support a load and will operate reliably.

b. Piezoelectric Depolarization Phenomena

The piezoelectric ceramic manufacturer, Clevite, was contacted and several technical discussions were had with their engineering personnel. The substance of these discussions were as follows:

The piezoelectric ceramic PZT-5H used in the clutch is a low coercivity material. This means that it is easily polarized and depolarized. Recommended voltage for use with this material is 3 volts per mil thickness or 180 volts per 60 mil slab. We have been restricted to the use of high voltages, 300 volts for setting the microactuator housing and 400 volts for operation, by the rigidity of the invar cantilever spring assembly and the dimension discrepancies in the clutch faces. These high voltages are used with the polarity reversed from that placed on the ceramic when it was poled. Such usage results in depolarization with attendant dimensional contraction. This dimensional change from fully polarized to depolarized state is -0.2% or 120 microinches per 60 mil ceramic. With twelve ceramics in series, a total contraction of 1440 microinches could result from complete depolarization. Depolarization can also occur if the piezoelectric material is mechanically compressed. It is felt that partial depolarization is responsible for the scatter in the dimensioning data and also responsible in part for the resultant loosening of fit after the microactuator has been operated.

The control of depolarization of the piezoelectric ceramic is being affected by:

- the fix for the cantilever constraint. The undercut invar spring allows the clutch to affect the same displacement with less voltage.

- the fixes for the clutch dimensional changes eliminates the need to electromechanically overstress the piezoelectric stacks during assembly and usage. These fixes also enable us to use wrung gage block stacks as controlled interference fit and parallelity spacers.

- the interference fit can be selected so that no more than 180 volts will be placed across the piezoelectric clutch stack

- the mechanical compression in the clutch stacks will be kept to a minimum commensurate with operational reliability.

c. Temperature Dependence

The sporadic nature of the operation of the microactuator device was originally traced to fluctuations in room temperature. The clutches had a tendency to drop out of the housings while standing in an upright position overnight. As a consequence of this, extensive investigations were done on the coefficients of linear expansion of the materials of construction and the determinations of clutch dimensioning across the faces as a function of temperature. This work uncovered the difference in dimensions between the top and bottom clutches on the same unit.

Correction of this discrepancy by precision lapping enabled us to cycle the clutch 250,000 times, correct some sporadicity, use the gage blocks technique for setting the housing and discover that the clutch takes a set. After the lapping operations, the clutch did not drop out of the housing. Apparently, the clutch drop was due to the non-parallelity of the housing ways. A discussion of the temperature dependence studies follows.

Examination of the materials of construction of the device revealed that there was a mismatch in the coefficients of linear expansion (invar -1.6 microinches/inch/°C) and the housing material (steel - 15 microinches/inch/°C).

Consequently, it was felt that lowering the temperature of the device would cause the housing to shrink fit the clutch and thereby restore operability and the ability to support a load. The opposite type of behavior proved to be true. Cooling caused the device to free and heating caused the device to lock. The only reasons for such behavior could be an inertia in temperature change between the housing and the clutch and/or a clutch construction material that has a larger coefficient of linear expansion than the steel.

Chemical and physical analyses of the invar used in the clutch show it to be of good grade for thermal stability applications. Chemical analyses check those of the supplier as follows:

Element	Monroe Forgings Inc.	Republic
	%	%
Ni	36.14	36.45
C	0.05	0.05
Mn	0.48	0.46

Experimental determination of the coefficient of linear expansion of the invar shows it to be 1.9 microinches/inch/°C.

Coefficient of expansion measurements on the finished clutches showed them to expand approximately 25 microinches/inch/°C. Measurements on the Clevite PZT-5H material as received from the vendor showed it to contract 44 microinches/inch/°C when heated. In order to clarify the observed anomaly, a telephone conversation was held with the Research Division of Clevite Corporation. Thermal expansion data for PZT-5H has not been determined. However, the data can be approximated in the following manner. The expansion data for poled PZT-5H should be similar to that of poled PZT-5A when a correction for the difference in the Curie points (temperature where piezoelectric effect is permanently destroyed) of both materials has been applied. The data are as follows:

	Curie Point (°C)
PZT-5A	365
PZT-5H	193
Difference	-172

Thermal Expansion Coefficient (α x 10^{-6}/°C

Poled PZT-5A

°C	First Heating α_3	Subsequent Heatings α_3
0	+2	+4
50	+2	+4
100	-6	+3
150	-7	+1
200	-7	-1.6
250	-6	-4.2

The approximated data for PZT-5H at room temperature should be the PZT-5A data at 192°C which shows the α_3 coefficient to be negative and to be very much dependent upon an initial heat treatement. The two microactuator clutches were heat conditioned at 50°C for one hour and have been tested for piezoelectric and temperature expansion effects. The piezoelectric constant d_{33} remains unchanged (593 x 10^{-12} meters/volt). The expansion across the clutch faces approximates 25 microinches/inch/°C. Telephone conversations have been held with the Clevite Research Division in regards to the differences in our experimental findings and their extrapolations in order to impress upon them the importance of reliable expansion data. Further investigations into the matching of expansion coefficients awaits the outcome of the conductive epoxy fix on the clutch assembly.

SECTION V

THE MICROACTUATOR HOUSING

The microactuator housing is constructed from two Starrett rectangular gage blocks which are cemented to two tool steel web blocks. The piezoelectric clutch faces mate with the ground and polished gage block faces. The force exerted by the clutch against the gage block face places the tool steel webs in tension. The controlled interference fit between the two opposite gage blocks and the opposing clutch faces govern the amount of load support the unit can sustain.

The rectangular gage blocks are an inexpensive way of obtaining a straight, high surface finish (2 microinches r.m.s), hard bearing surface. These gage blocks measure 0.550000" x 0.357" x 1.380". The distance, 0.550000" (68°F) between the ground and polished surfaces is kept within a tolerance of $^{+4}_{-2}$ microinches. The coefficient of linear expansion of the blocks is 6.4 microinches per inch per °F. Blocks are available in many sizes and can be wrung together to form thousands of combinations, all of which are some multiple of 25 microinches. The basic building blocks for microinch dimensioning differ from each other by 25 microinches, i.e., 0.100025", 0.100050", 0.100075", and 0.100100".

The tool steel webs are made of A-1 tool steel. Its nominal coefficient of linear expansion approximates 10 microinches per inch per °F. The webs were originally 1/8" thick. They have been thickened to 3/8" thickness in order to minimize the elongation due to the tensile forces. A sample calculation of the elgonation is as follows:

(1) the normal force acting against the gage blocks in order to support a load of 30 pounds would be 70 pounds

(2) the tensile force in each web acting against a cross-sectional area of 1/8" x 1-3/16" (0.15 in^2) is 35 pounds. The modulus of elasticity of the steel is 30 x 10^6 pounds per square inch

$$\text{modulus of elasticity} = \frac{\text{force per unit area}}{\text{elongation per unit length}}$$

$$\text{elongation per unit length} = \frac{\text{force per unit area}}{\text{modulus of elasticity}}$$

$$\text{elongation per unit length} = \frac{\frac{35\#}{.15\ in^2}}{30 \times 10^6 \#/in^2}$$

$$= \frac{233.3}{30 \times 10^6} \qquad 7 \times 10^{-6} in/in$$

So we see that this microactuator web will elongate 7 microinches when the clutch (1" across) exerts this force (70 pounds). There will be a trade-off of allowable elongation versus the increase in weight. Since the cantilever constraint in the original clutch limited the interference fit to 20 microinches, this elongation accounts for 33% reduction in interference fit. The cross-sectional area of the web was increased threefold in order to decrease this loss to 11%.

Two different methods of joining the webs to the gage blocks were tried. Since the gage blocks are hardened steel the only practical way for drilling holes for pinning was by use of an Elox machine. This method was tried and discarded because the holes tended to walk while being lapped for the pin.

The other method, use of an epoxy adhesive, proved successful only after certain pitfalls were circumvented. The original method for joining the webs to the gage blocks made use of the epoxy cement, Hysol 1C. This cement was found to give due to the high shear stresses placed upon it when the 300 volts, used to compress the clutches during the epoxy cure, was removed. The use of Hysol 1C with the new method of fitting the clutch was equally unsatisfactory. The mixing of the epoxy with the catalyst generated heat which changed the housing dimensions during the setting and cure. The handling of the materials with the hands and the heat from the epoxy increased the dimensions from 100-200 microinches.

It should be noted also here that engineering data on adhesives is virtually non-existent. Currently, we use a hard, tough epoxy cement that does not have the drawbacks of the Hysol 1C. The housings made with this cement have kept their dimensions in the millionths of an inch place and their parallelity for over 500,000 clutch cycles.

The effect of temperature changes on the functioning of the microactuator device await the outcome of the fix on the epoxy cement used to form the piezoelectric ceramic stacks. Ideally, the coefficients of linear expansion of the microactuator housing web material should match as close as possible the coefficient of linear expansion of the piezoelectric ceramic material.

SECTION VI

CONCLUSIONS

The Republic Aviation Division design concept for the microinch actuator has been proven to have definite merit. The nature of the piezoelectric action resulting in linear displacements adjustable from 5×10^{-7} inches to 20×10^{-6} inches, adequate force levels and a frequency response of one kilocycle have proven ideal for the special requirements to be satisfied by the microinch actuator. However, with any device whose design and fabrication push the state-of-the-art, problem areas tend to arise which require solution before the instrument becomes a functional, reliable, reality.

These problem areas manifested themselves as anomalies in device operation, specifically, sporadic operation, temperature dependence, spurious movements and the inability to support a load. The solution of the problem of a sporadic operation and temperature dependence was effected in part by undercutting the cantilever web on the piezoelectric clutch, precision relapping of the clutch faces assuring parallelity, the use of the gage block technique for fitting the housing to the piezoelectric clutch with a controlled interference fit and assured parallelity of ways and by depolarization control of the piezoelectric ceramics.

The remaining problem area, spurious movement and inability to support a load should be corrected by the rebuilding of the piezoelectric clutches with a high strength non-elastomeric epoxy cement. The use of this cement on the micro-actuator housing has resulted in a perfect housing which has not changed dimensions in 500,000 clutch cycles. Indeed, because of these fixes, the microinch actuator has successfully walked over a one-quarter inch length in forward and reverse directions for 250,000 cycles. It should be noted that a precision optics device such as the microinch actuator requires a finesse in fabrication and usage which can only come about by an understanding of the physical laws governing its behavior coupled with an understanding of the materials technology.

SECTION VII

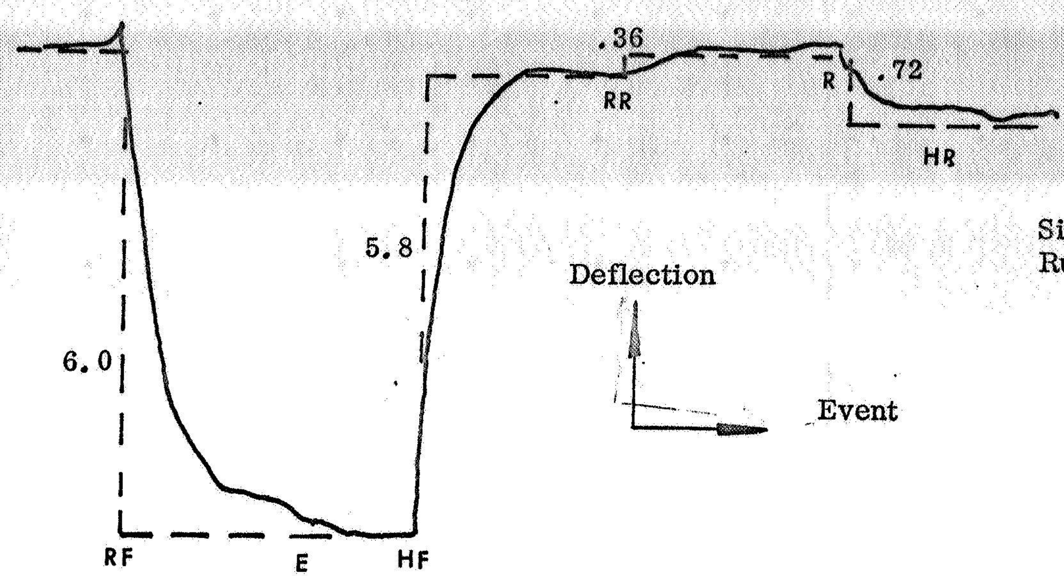
FUTURE WORK

The efforts of the Republic Aviation Division on the microinch actuator have been rewarding insofar as these efforts have identified and corrected the behavorial anomalies in the microinch actuator device. However, they have also revealed some minor design deficiencies. The correction of these deficiencies coupled with an understanding of possible problem areas peculiar to aerospace usage, should result in an aerospace qualified device. The Republic Aviation Division will submit an unsolicited proposal for a redesign contract for an aerospace qualified microinch actuator device to National Aeronautics and Space Administration, Langley Research Center.

APPENDIX

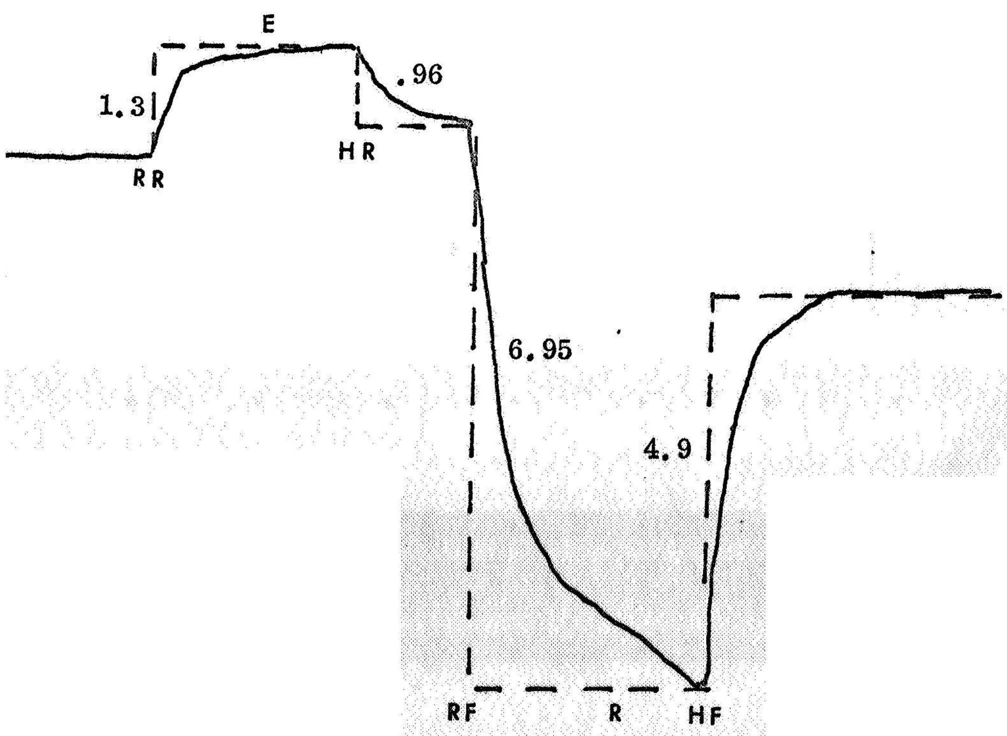
DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Side I
Run 4

Scale
2 μ in.

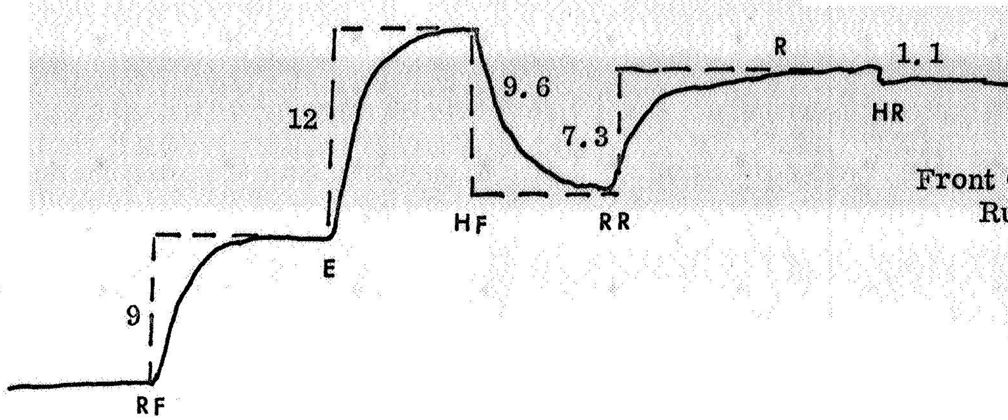


Side I
Run 2

APPENDIX

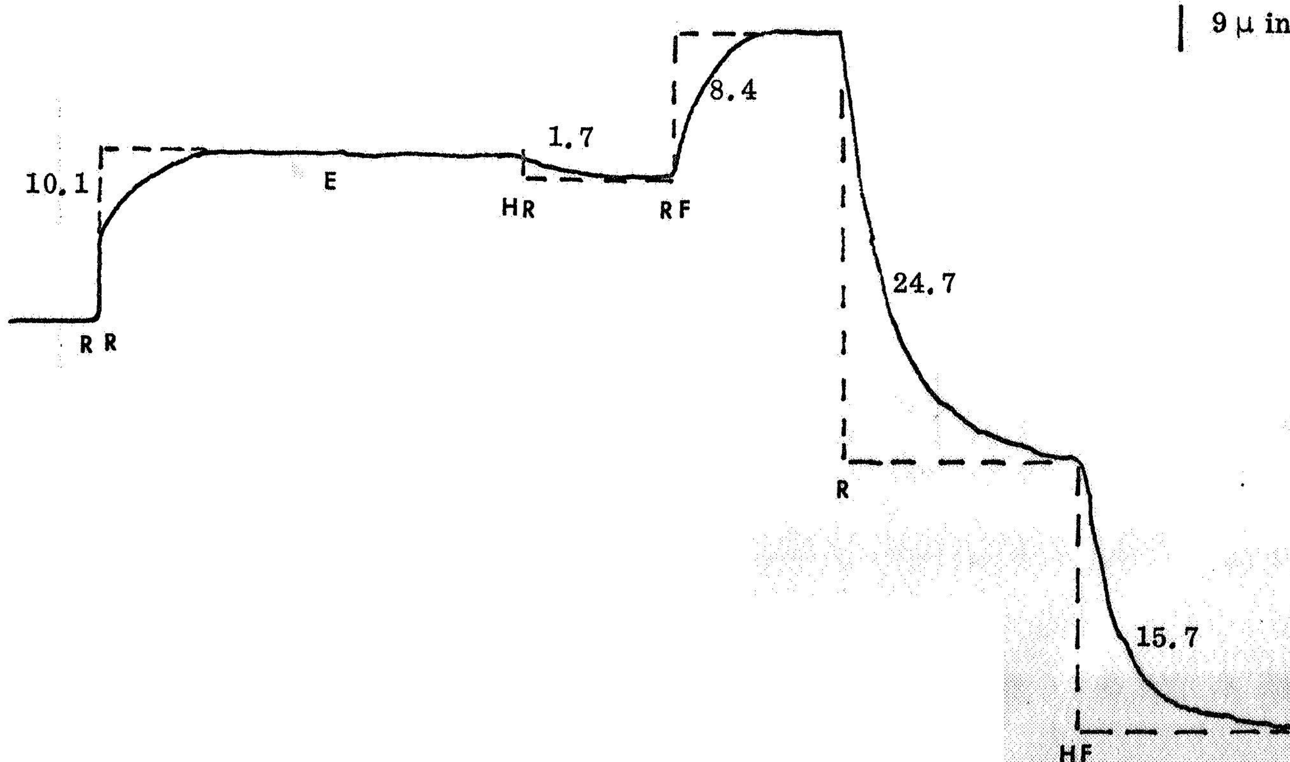
DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Front Clutch H
Run 5

Scale
9 μ in.

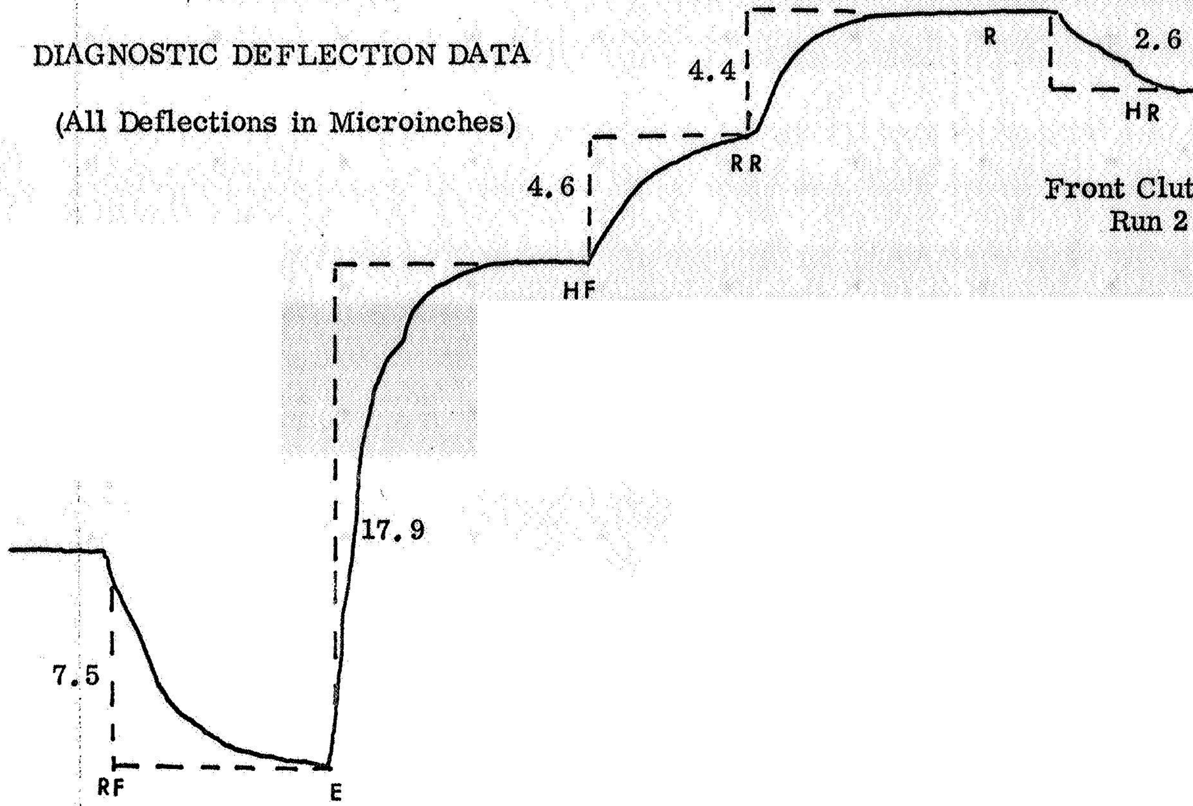


Front Clutch H
Run 1

APPENDIX

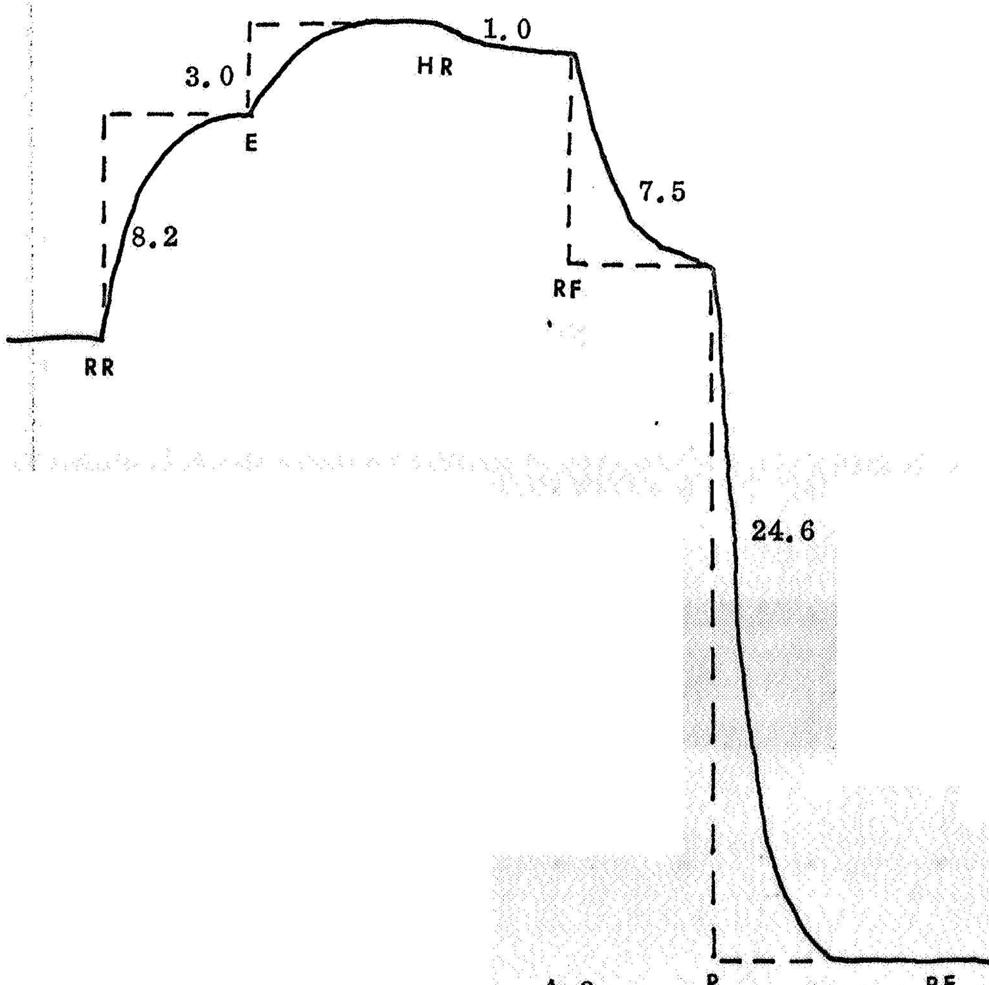
DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Front Clutch G
Run 2

Scale
5 μ in.

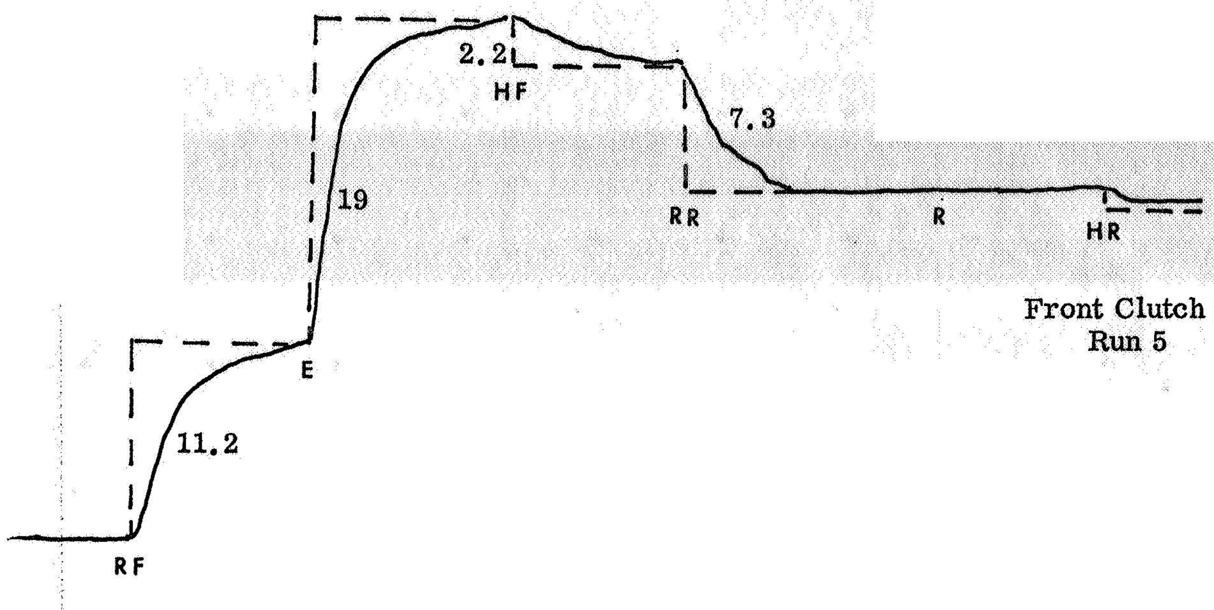


Front Clutch G
Run 4

APPENDIX

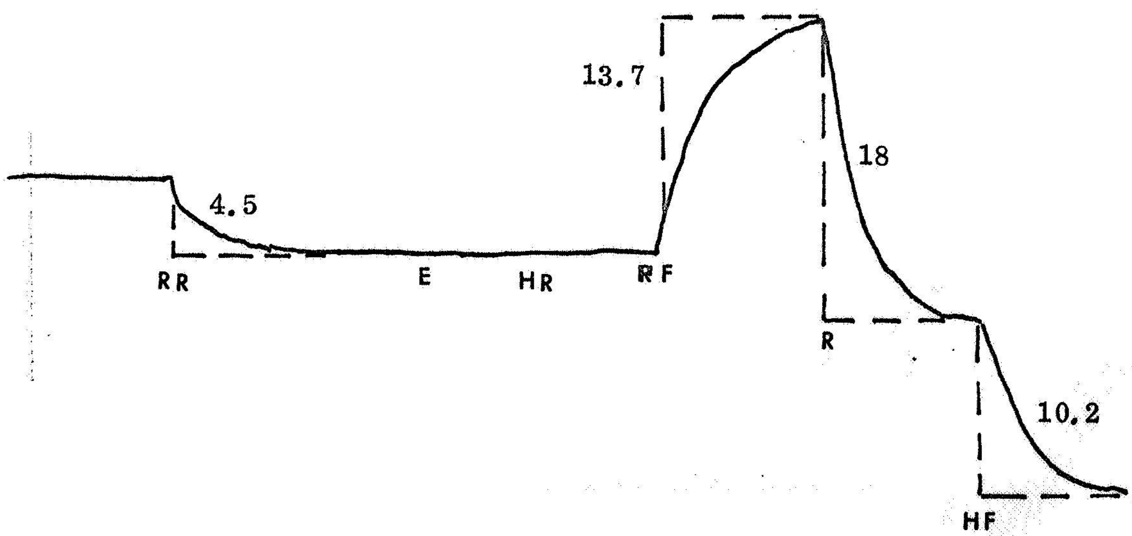
DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Front Clutch F
Run 5

Scale
9 μ in.

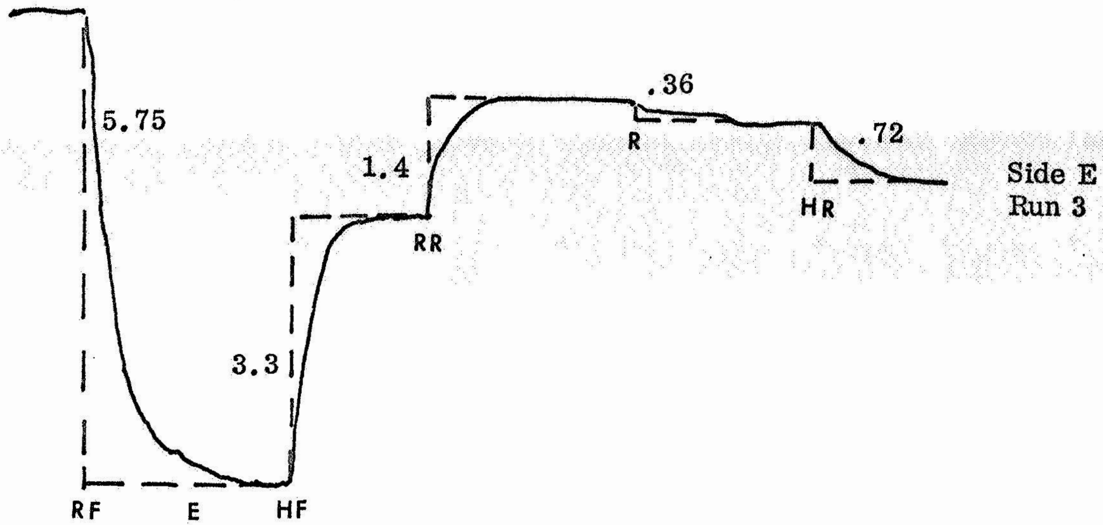


Front Clutch F
Run 2

APPENDIX

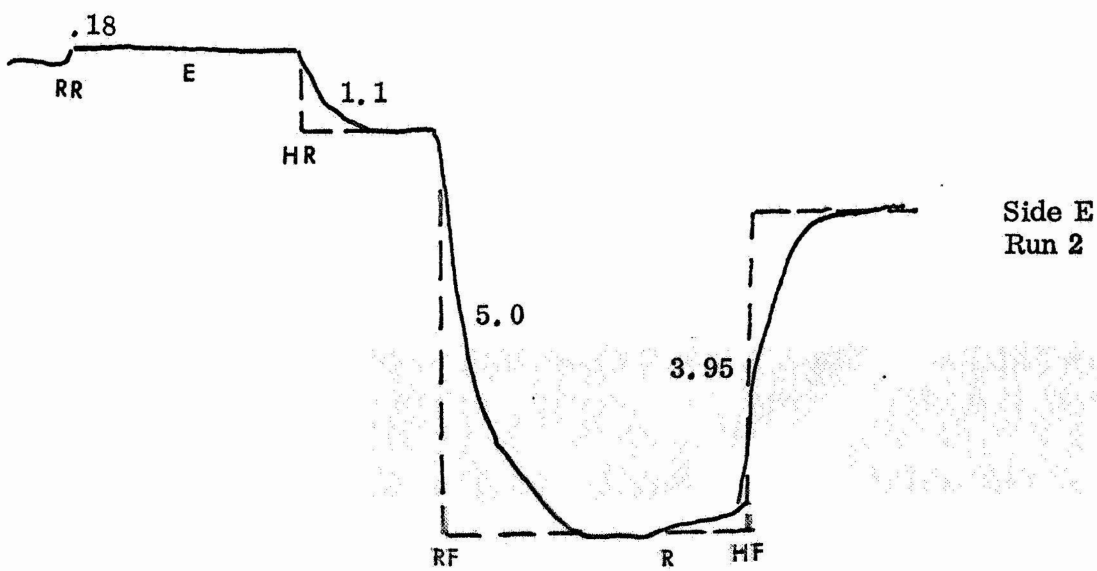
DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Scale

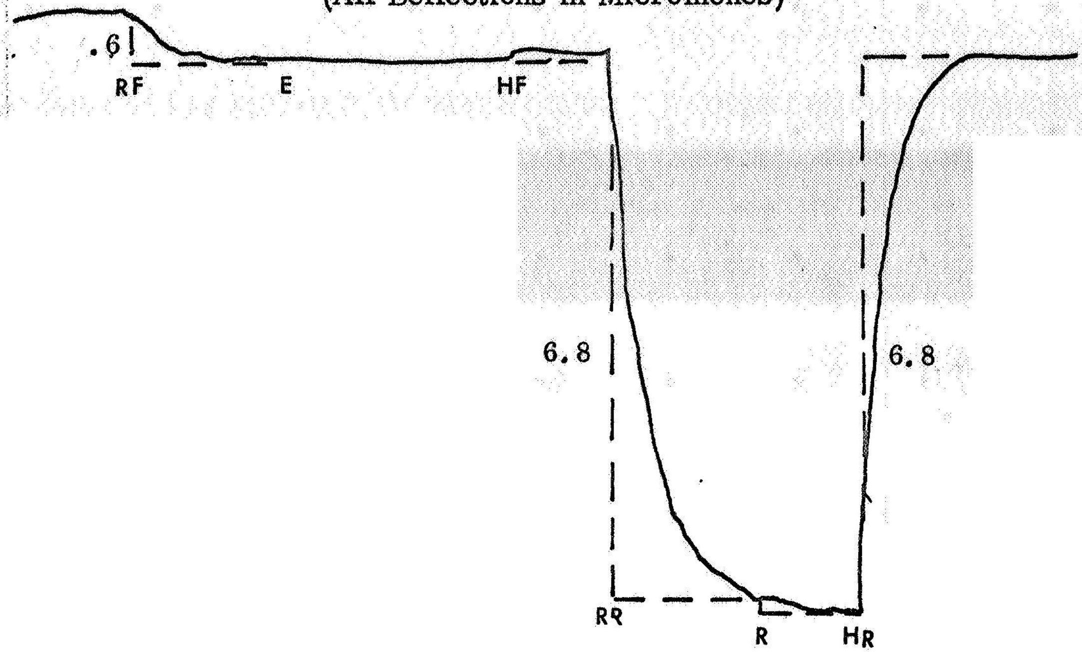
2 μ in.



APPENDIX

DIAGNOSTIC DEFLECTION DATA

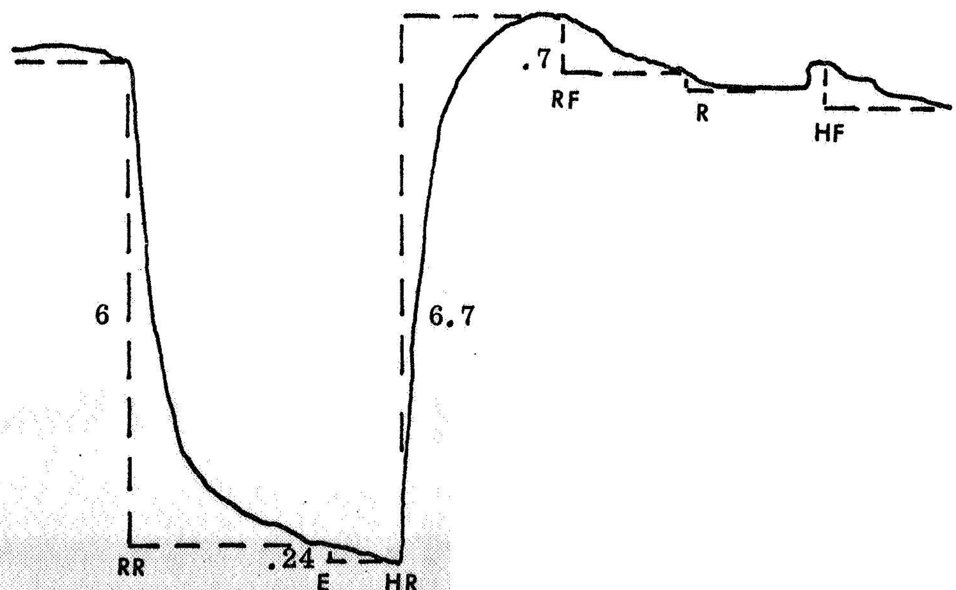
(All Deflections in Microinches)



Side J
Run 3

Scale

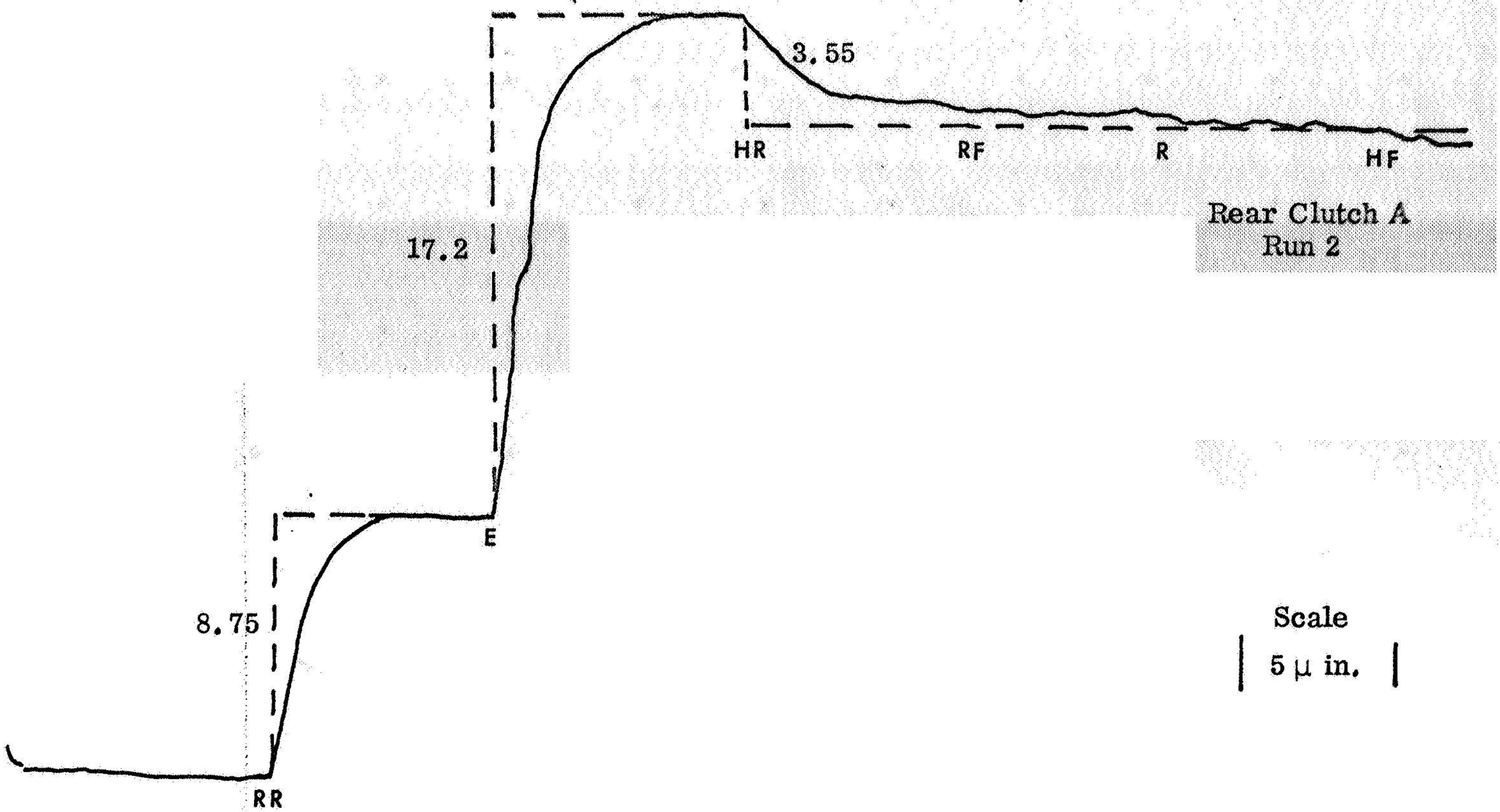
2 μ in.

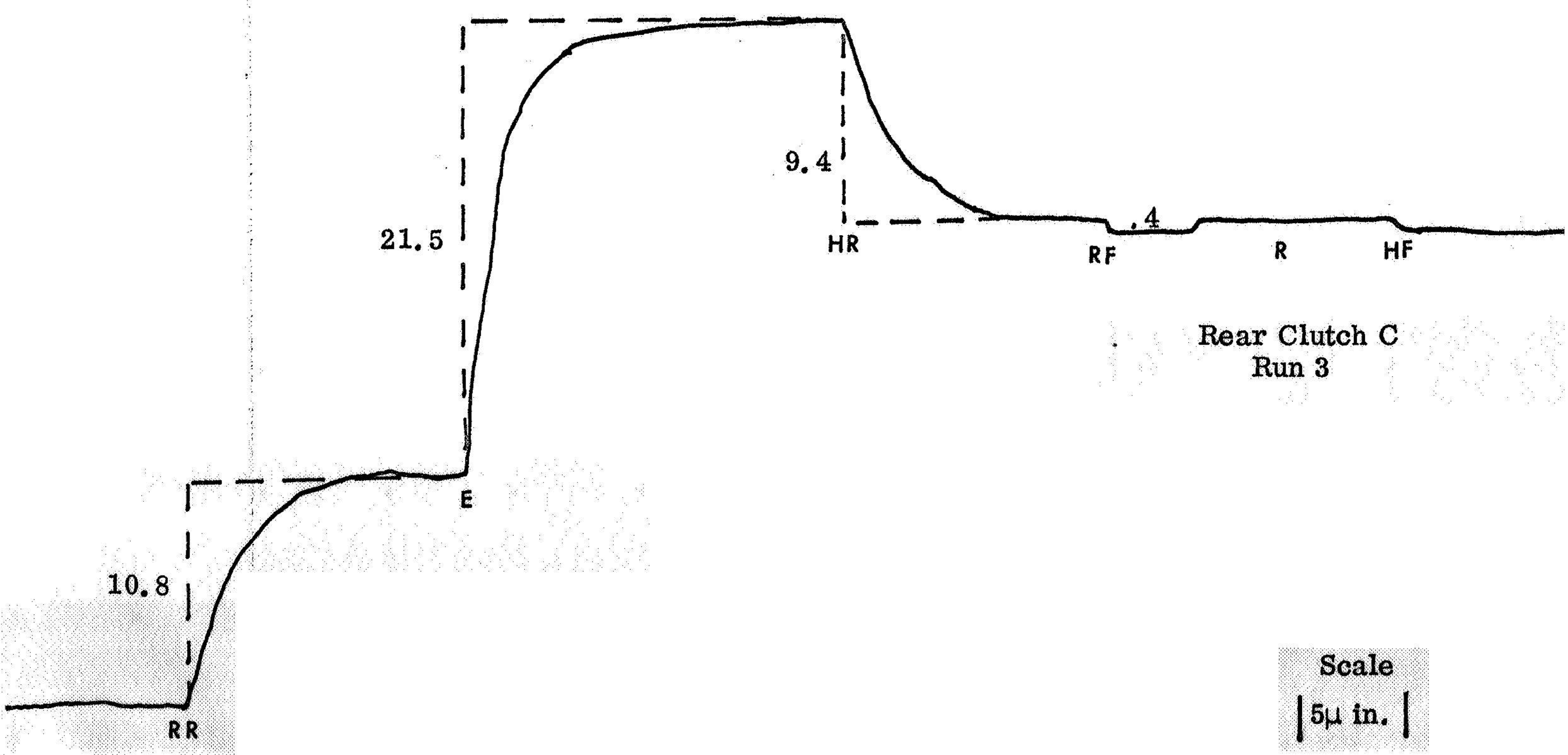


Side J
Run 1

DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)

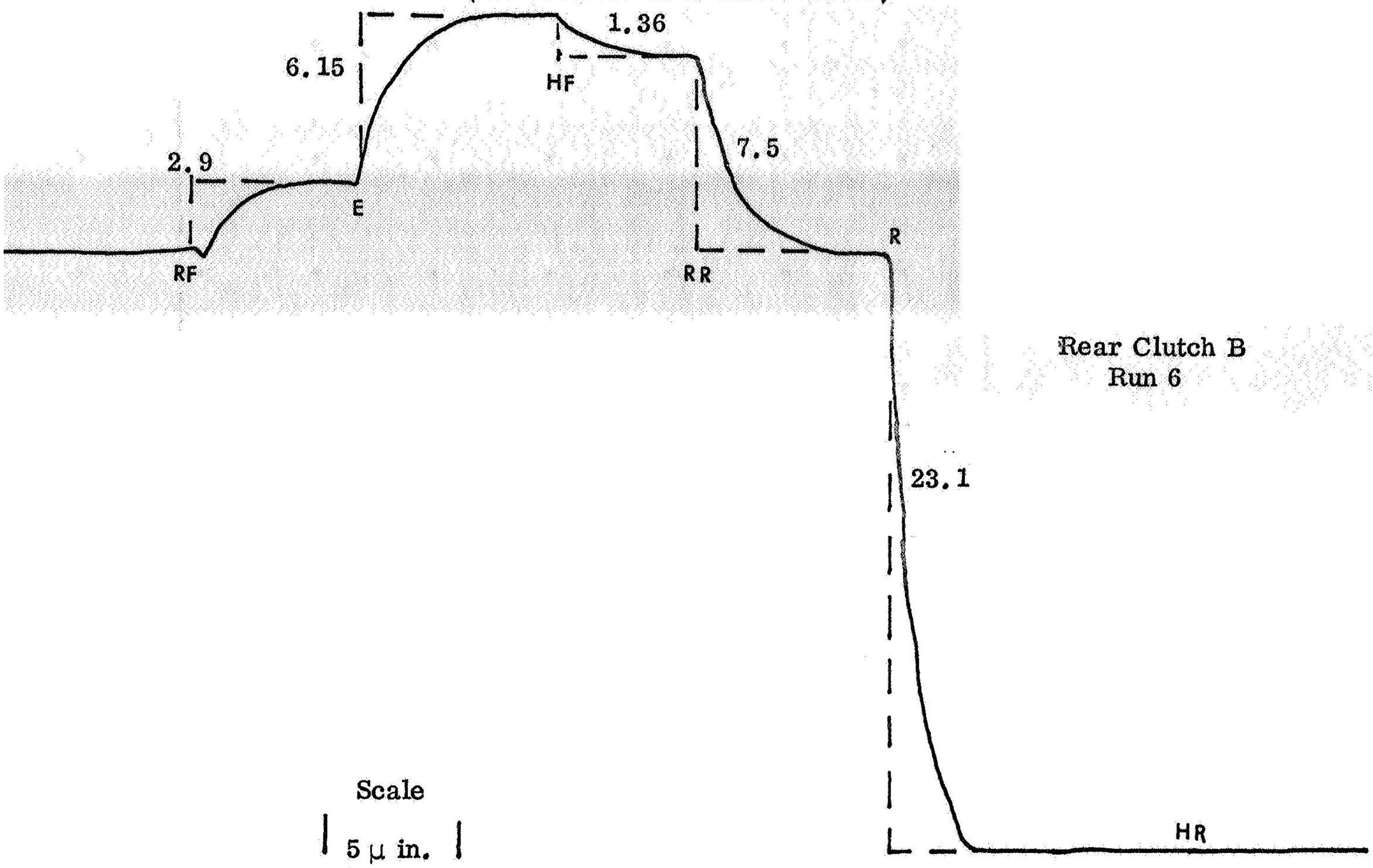




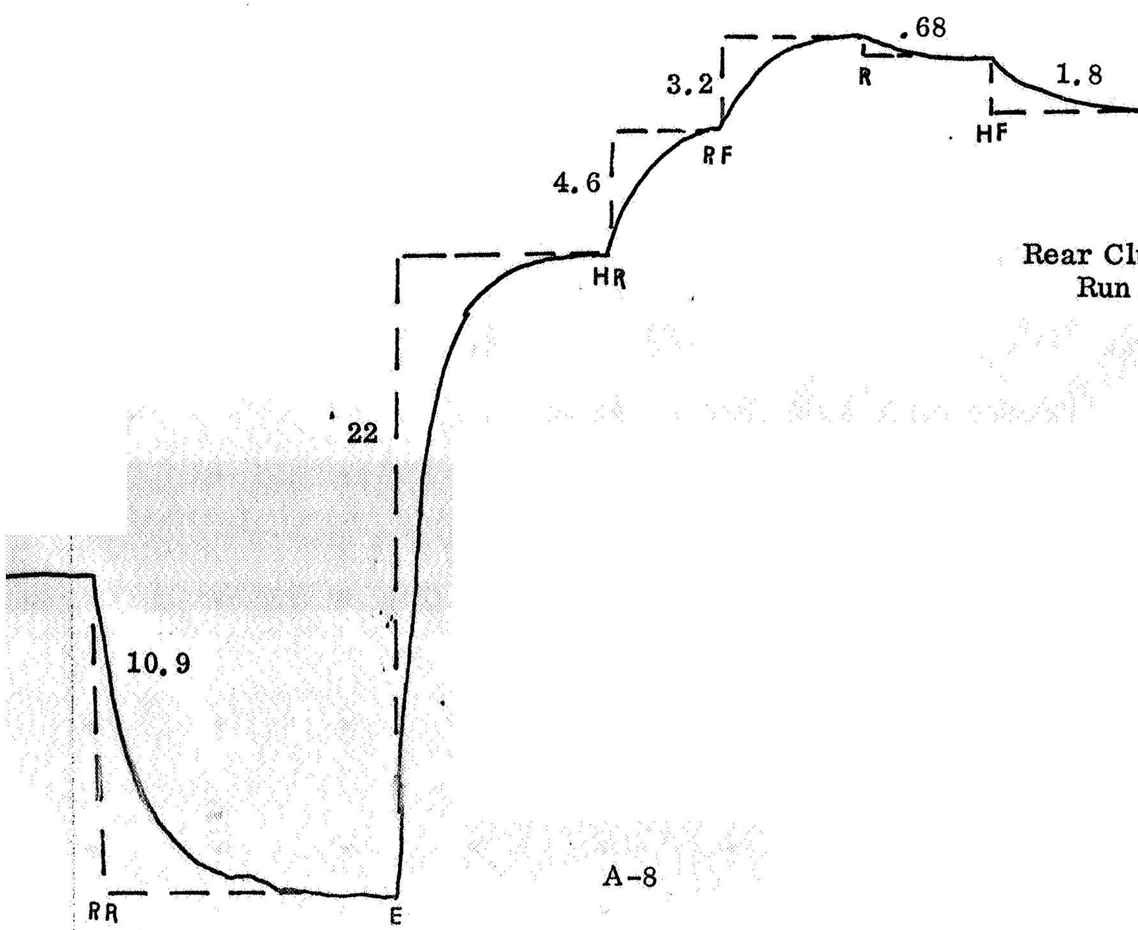
APPENDIX

DIAGNOSTIC DEFLECTION DATA

(All Deflections in Microinches)



Rear Clutch B
Run 6

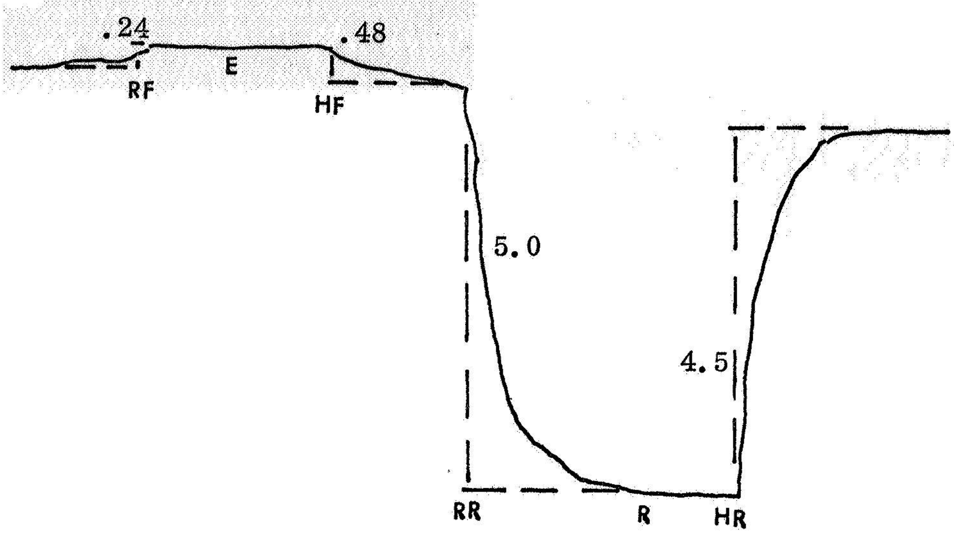


Rear Clutch B
Run 2

APPENDIX

DIAGNOSTIC DEFLECTION DATA

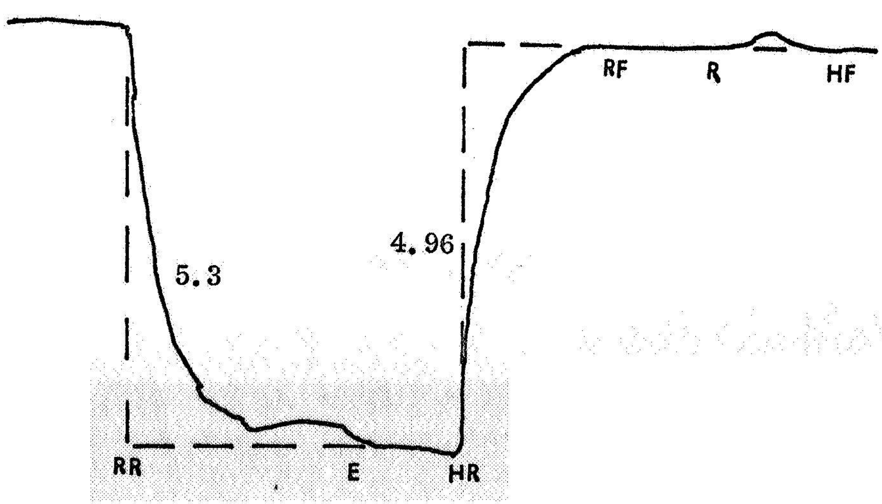
(All Deflections in Microinches)



Side D
Run 3

Scale

| 2.0 μ in. |



Side D
Run 2

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